Star Cluster Evolution: From young massive star clusters to old globulars

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Summary. Young, massive star clusters are the most notable and significant end products of violent star-forming episodes triggered by galaxy collisions, mergers, and close encounters. The question remains, however, whether or not at least a fraction of the compact YMCs seen in abundance in extragalactic starbursts, are potentially the progenitors of globular cluster (GC)-type objects. However, because of the lack of a statistically significant sample of similar nearby objects we need to resort to either statistical arguments or to the painstaking approach of case by case studies of individual objects in more distant galaxies. Despite the difficulties inherent to addressing this issue conclusively, an ever increasing body of observational evidence lends support to the scenario that GCs, which were once thought to be the oldest building blocks of galaxies, are still forming today.

1 Young massive star clusters as proto-globular clusters

The production of luminous, massive yet compact star clusters (YMCs; often with masses $m_{\rm cl} \geq 10^5 {\rm M}_\odot$) seems to be a hallmark of the most intense starbursts. YMCs are therefore important as benchmarks of cluster formation and evolution. They are also important as tracers of the (stellar) initial mass function (IMF) and other physical characteristics in starbursts. The key properties of YMCs have been explored in starburst regions in several dozen galaxies, both in normal spirals and in gravitationally interacting galaxies.

The question remains, however, whether or not at least some of the YMCs observed in extragalactic starbursts might survive for a Hubble time. If we could settle this issue convincingly, one way or the other, the implications would be far-reaching for a wide range of astrophysical questions, including (but not limited to) our understanding of the process of galaxy formation, assembly and evolution, and the process and conditions required for star and star cluster formation.

2 Resolution of the evolutionary question

The evolution of young clusters depends crucially on their stellar IMF: if the IMF is too shallow, i.e., if the clusters are significantly depleted in low-mass stars compared to, e.g., the solar neighbourhood, they will likely disperse within about a Gyr of their formation (e.g., Gnedin & Ostriker 1997; Goodwin 1997; Smith & Gallagher 2001; Mengel et al. 2002). At present, there are two principal approaches in which one can attempt to address the underlying IMFs of extragalactic YMCs [but see also de Grijs et al. (2005a) for an alternative approach].

2.1 The Cluster Luminosity Function: the case of M82

In de Grijs et al. (2003a,b) we reported the discovery of an approximately log-normal cluster luminosity and mass function (CLF, CMF) for the roughly coeval star clusters at the intermediate age of ~ 1 Gyr in M82's fossil starburst region "B". This provided the first deep CLF (CMF) for a star cluster population at intermediate age, which thus serves as an important benchmark for theories of the evolution of star cluster systems [see also Goudfrooij et al. (2004) for a related important result for NGC 1316, at ~ 3 Gyr].

A substantial series of papers on the young Large Magellanic Cloud cluster system (with ages $\leq 2 \times 10^9$ yr), starting with the seminal work by Elson & Fall (1985), seem to imply that the CLF of YMCs is well described by a power law [but see de Grijs & Anders (2006) for caveats]. On the other hand, for old globular cluster (GC) systems with ages $\geq 10^{10}$ yr, the CLF shape is well established to be roughly log-normal, and almost universal among local galaxies. This type of observational evidence has led to the popular, but thus far mostly speculative theoretical prediction that not only a power-law, but *any* initial CLF (CMF) will be rapidly transformed into a log-normal distribution because of *(i)* stellar evolutionary fading of the lowest-luminosity (mass) objects to below the detection limit; and *(ii)* disruption of the low-mass clusters due both to interactions with the gravitational field of the host galaxy, and to internal two-body relaxation effects leading to enhanced cluster evaporation.

From our detailed analysis of the expected evolution of CMFs starting from initial log-normal and initial power-law distributions (de Grijs et al. 2005b), we conclude that our observations of the M82 B CMF are inconsistent with a scenario in which the 1 Gyr-old cluster population originated from an initial power-law mass distribution. This applies to a large range of "characteristic" cluster disruption time-scales. Our conclusion is supported by arguments related to the initial density in M82 B, which would be unphysically high if the present cluster population were the remains of an initial power-law distribution (particularly in view of the effects of cluster "infant mortality", which require large excesses of low-mass unbound clusters to be present at the earliest times).

In de Grijs et al. (2003c) we showed that the CMFs of YMCs in many different environments are well approximated by power laws with slopes $\alpha \simeq -2$. However, except for the intermediate-age cluster systems in M82 B and NGC 1316 (Goudfrooij et al. 2004), the *expected* turn-over (or peak) mass (based on comparisons with present-day GC systems and taking evolutionary fading into account) in most YMC systems observed to date occurs close to or below the observational detection limit, simply because of their greater distances and shallower observations. As such, these results are not necessarily at odds with each other, but merely hindered by observational selection effects.

2.2 High-resolution spectroscopy: individual cluster analysis

With the ever increasing number of large-aperture ground-based telescopes equipped with state-of-the-art high-resolution spectrographs and the wealth of observational data provided by the *Hubble Space Telescope*, we may now finally be getting close to resolving the potentially far-reaching issue of YMC-to-GC evolution conclusively. To do so, one needs to obtain *(i)* high-resolution spectroscopy, in order to obtain dynamical mass estimates, and *(ii)* high-resolution imaging to measure their sizes (and luminosities). As a simple first approach, one could then construct diagnostic diagrams of YMC mass-to-light ratio vs. age, and compare the YMC locations in this diagram with models of "simple stellar populations" (SSPs) using a variety of IMF descriptions (cf. Smith & Gallagher 2001; Mengel et al. 2002; Bastian et al. 2006). However, such an approach, while instructive, has serious shortcomings:

(i) In this simple approach, the data can be described by *both* variations in the IMF slope *and* variations in a possible low-mass cut-off; the models are fundamentally degenerate for these parameters.

(ii) While the assumption that these objects are approximately in virial equilibrium is probably justified at ages greater than a few $\times 10^7$ yr (at least for the stars dominating the light), the *central* velocity dispersion (as derived from luminosity-weighted high-resolution spectroscopy) does not necessarily represent a YMC's total mass. It is now well-established that almost every YMC exhibits significant mass segregation from very early on, so that the effects of mass segregation must be taken into account when converting central velocity dispersions into dynamical mass estimates (see also Lamers et al. 2006; J.J. Fleck et al., in prep.).

(iii) With the exception of a few studies (e.g., M82-F; Smith & Gallagher 2001), the majority of YMCs thus far analysed in this way have ages around 10 Myr. Around this age, however, red supergiants (RSGs) appear in realistic stellar populations. Unfortunately, the model descriptions of the RSG phase differ significantly among the various leading groups producing theoretical stellar population synthesis codes (Padova vs. Geneva vs. Yale), and therefore the uncertainties in the evolutionary tracks are substantial.

3 The current verdict?

It may appear that a fair fraction of the ~ 10 Myr-old YMCs that have been analysed thus far may be characterised by unusual IMFs, since their loci in the diagnostic diagram are far removed from any of the "standard" SSP models (see, e.g., Bastian et al. 2006). However, Bastian & Goodwin (2006) recently showed that this is most likely an effect of the fact that the velocity dispersions of these young objects do not adequately trace their masses. They are instead strongly affected by the effects of gas expulsion due to supernova activity and massive stellar winds. In this respect, it is encouraging to see that the older clusters (i.e., older than M82-F, a few $\times 10^7$ yr) seem to conform to "normal" IMFs; by those ages, the clusters' velocity dispersions seem to represent the underlying gravitational potential much more closely.

We recently reported the discovery of a extremely massive, but old (12.4 ± 3.2 Gyr) GC in M31, 037-B327, that has all the characteristics of having been an exemplary YMC at earlier times (Ma et al. 2006). In order to have survived for a Hubble time, we conclude that its stellar IMF cannot have been top-heavy, i.e., characterized by a low-mass cut-off at $m_\star \geq 1$ M$_\odot$, as sometimes advocated for current YMCs (e.g., Smith & Gallagher 2001). Using this constraint, and a variety of SSP models, we determine a photometric mass for 037-B327 of $M_{\rm GC} = (3.0 \pm 0.5) \times 10^7$ M$_\odot$, somewhat depending on the SSP models used, the metallicity and age adopted and the IMF representation. In view of the large number of free parameters, the uncertainty in our photometric mass estimate is surprisingly small. This mass, and its relatively small uncertainties, make this object the most massive star cluster of any age in the Local Group. As a surviving "super" star cluster, this object is of prime importance for theories aimed at describing massive star cluster evolution.

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